Towards an Understanding of the New Charm and Charm-Strange Mesons

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Abstract. The observation of the $D_{sJ}^*(2317)$, $D_{sJ}(2460)$, and SELEX $D_{sJ}^*(2632)$ states with properties differing considerably from what was expected has led to a renewed interest in hadron spectroscopy. In addition to these states, non-strange partners of the D_{sJ} states have also been observed. Understanding the D_0^* and D_1' states can provide important insights into the D_{sJ} states. In this contribution I examine quark model predictions for the D_0^* and D_1' states and discuss experimental measurements that can shed light on them. I find that these states are well described as the broad, $j = 1/2$ non-strange charmed P-wave mesons. In the latter part of this writeup I discuss the $c\bar{s}$ possibilities for the SELEX $D_{sJ}^*(2632)$ and measurements that can shed light on it.

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1. Introduction

The last eighteen months have been exciting times for hadron spectroscopists with the first observation of many charmed and charmonium states. It started with the observation of the $D_{sJ}^*(2317)$ [1] which was described as having properties "quite different from those predicted by quark potential models". The $D_{sJ}(2460)$[2] was observed shortly thereafter with similar discrepancies between theory and experiment. To understand the nature of the discrepancies we note that the four $L = 1$ P-wave mesons can be grouped into two doublets characterized by the angular momentum of the light quark; $j = 3/2$, $1/2$. The $j = 3/2$ $c\bar{s}$ states were predicted to be relatively narrow and are identified with the $D_{s1}(2536)$ and $D_{s2}(2573)$ states while the D_{s0}^* and D_{s1}' $j = 1/2$ states were expected to have large S-wave widths decaying to DK and D^*K respectively[3]. However, the states observed by Babar and CLEO are below $D^{(*)}K$ threshold and are very narrow. This has led to considerable theoretical speculation that these states may be something new such as multiquark states or meson-molecules [4]. My view is that the $D_{sJ}^{(*)}$ states are conventional $q\bar{q}$ states with their masses shifted due to coupling to the nearby DK and D^*K open channels. Diagnostic tests have been proposed to help understand the nature of these newly discovered states [4, 5, 6, 7]. In addition, the non-strange $j = 1/2$ P-wave states, D_0^* and D_1', have been observed [8, 9, 10] and comparing their observed properties with theoretical predictions can give us some sense of how reliable the models are [4, 11]. The first part of this writeup examines quark model predictions of properties of the charm and charm-strange P-wave mesons and some diagnostic tests of the $q\bar{q}$ explanation.

The most recent addition to the family of charm meson misfits is the $D_{sj}^*(2632)$ state observed

by the SELEX collaboration [12]. Again, there has been considerable speculation about what this state might be. In the second part of this writeup I discuss the quark model possibilities and outline some measurements that can be used to test them [13, 14].

2. The Charmed P-wave Mesons

Almost all the theoretical effort has been devoted to explain the $D_{sJ}^{(*)}$ states. The non-strange partners have received almost no attention although they also contain important spectroscopic information and could hold the key to understanding the $D_{sJ}^{(*)}$'s or at least tell us how reliable our models are.

The measured properties of the $L = 1$ charm mesons are summarized in Table 1 along with quark model predictions [3, 11, 15]. The quark model gives a P-wave cog that is ~ 40 MeV too high but the splittings are in very good agreement with the measured masses. The width predictions are given for the pseudoscalar emission model with the flux-tube model giving qualitatively similar results [3]. We note that Belle [8] and FOCUS [9] measure $\Gamma(D_2^{*0}) = 37 \pm 4.0$ MeV and $\Gamma(D_1^0) = 23.7 \pm 4.8$ MeV which are larger than the PDG values. They attribute differences with older results to taking into account interference with the broader D states. Overall the agreement between theory and experiment is quite good. Note that the physical $D_1^{(\prime)}$ states are linear combinations of the $^3P_1$ and $^1P_1$ states so that the good agreement for the decay widths reflects a successful prediction for the $1^3P_1 - 1^1P_1$ mixing angle.

Table 1. Comparison of Quark Model Predictions[3,11,15] to Experiment for the L=1 Charm Mesons.

State	Mass (MeV)		Width (MeV)	
	Theory^a	Expt	Theory^{b,7,10}	Expt
D_2^*	2460	2459 ± 2 ^{c}	54	23 ± 5 ^{c}
D_1	2418	2422 ± 1.8 ^{c}	24	$18.9^{+4.6}_{-3.5}$ ^{c}
D_1'	2428	2438 ± 30 ^{d}	250	329 ± 84 ^{d}
D_0^*	2357	2308 ± 36 ^{e}	280	276 ± 66 ^{e}

^{a} The P-wave cog [3, 15] was shifted down 42 MeV.
^{b} Using the masses from column 2.
^{c} Particle Data Group [16]
^{d} Average of the Belle [8] and CLEO [10] $D_1'^0$ measurements
^{e} Belle Collaboration [8]

Radiative transitions probe the internal structure of hadrons [5, 6, 7]. Table 2 gives the quark model predictions for E1 radiative transitions between the $1P$ and $1S$ charm mesons [11]. The $D_2^{*0} \to D^{*0}\gamma$, $D_1^0 \to D^{*0}\gamma$ and $D_1^0 \to D^0\gamma$ transitions should be observable. The latter two are of particular interest since the ratio of these partial widths measure the $^3P_1 -^1 P_1$ mixing angle in the charm meson sector which is a good test of how well the Heavy Quark Limit is satisfied.

The overall conclusion is that the quark model describes the P-wave charm mesons quite well and models invoked to describe the $D_{sJ}^*(2317)$ and $D_{sJ}(2460)$ states should also explain their non-strange charm meson partners. Better data would further test the models.

3. The Charm-Strange P-wave Mesons

Turning to the D_{sJ} states, the narrow $j = 3/2$ states are identified with the $D_{s1}(2536)$ and $D_{s2}(2573)$ with their observed properties in good agreement with quark model predictions[3, 15].

Table 2. Partial widths and branching ratios for E1 transitions between $1P$ and $1S$ charm mesons. The widths are given in keV unless otherwise noted. The M_i and the total widths used to calculate the BR's are taken from Table 1. The matrix elements are calculated using the wavefunctions of Ref. 15.

Initial state	Final state	M_i (GeV)	M_f (GeV)	k (MeV)	$\langle 1P\|r\|nS\rangle$ (GeV^{-1})	Width (keV)	BR
D_2^{*+}	$D^{*+}\gamma$	2.459	2.010	408	2.367	57	0.25%
D_2^{*0}	$D^{*0}\gamma$	2.459	2.007	411	2.367	559	2.4%
D_1^+	$D^{*+}\gamma$	2.422	2.010	377	2.367	8.8	5×10^{-4}
	$D^+\gamma$	2.422	1.869	490	2.028	58	0.3%
D_1^0	$D^{*0}\gamma$	2.422	2.007	380	2.367	87	0.5%
	$D^0\gamma$	2.422	1.865	493	2.028	571	3.0%
$D_1^{\prime +}$	$D^{*+}\gamma$	2.428	2.010	382	2.367	37	10^{-4}
	$D^+\gamma$	2.428	1.869	494	2.028	15	4×10^{-5}
$D_1^{\prime 0}$	$D^{*0}\gamma$	2.428	2.007	385	2.367	369	0.1%
	$D^0\gamma$	2.428	1.865	498	2.028	144	4×10^{-4}
D_0^{*+}	$D^{*+}\gamma$	2.357	2.010	321	2.345	27	10^{-4}
D_0^{*0}	$D^{*0}\gamma$	2.357	2.007	324	2.345	270	0.1%

The $j=1/2$ states were predicted to be broad and to decay to DK and D^*K and were not previously observed. But the $D_{sJ}^*(2317)$ is below DK threshold and the $D_{sJ}(2460)$ is below D^*K threshold so the only allowed strong decays are $D_{sJ}^{(*)} \to D_s^{(*)}\pi^0$ which violate isospin and are expected to have small widths $\mathcal{O}(10)$ keV [5, 6, 7]. As a consequence, the radiative transitions are expected to have large BR's and are an important diagnostic tool to understand the nature of these states [5, 6, 7]. Although there are discrepancies between the quark model predictions and existing measurements they can be accomodated by the uncertainty in theoretical estimates of $\Gamma(D_{sJ}^{(*)} \to D_s^{(*)}\pi^0)$ and by adjusting the $^3P_1 -^1 P_1$ mixing angle for the D_{s1} states. As in the case of the D_1 states, the radiative transitions to D_s and D_s^* can be used to constrain the $^3P_1 -^1 P_1$ $(c\bar{s})$ mixing angle.

The problems with the newly found D_{sJ} states are the mass predictions. Once the masses are fixed the narrow widths follow. My view is that the strong coupling to DK (and D^*K) is the key to solving this puzzle. A number of people have studied this and have found that coupled channel effects lead to the required mass shifts [17]. Unfortunately, coupled channel effects also appear to lead to comparable shifts in states that were previously in good agreement with experiment [18]. So it is still an open question whether coupled channel effects can account for the discrepancy between quark model predictions for the D_{sJ} masses and experiment.

4. Options for the $D_{sJ}^*(2632)$

The SELEX collaboration recently observed a narrow charm-strange meson decaying into $D_s^+\eta$ and D^0K^+ final states in the ratio of $\Gamma(D^0K^+)/\Gamma(D_s^+\eta) = 0.16 \pm 0.06$ with $M = 2632.6 \pm 1.6$ MeV/c^2 and $\Gamma < 17$ MeV/c^2 at 90% C.L. [12]. A number of possible assignments have been suggested: a conventional $2^3S_1(c\bar{s})$ state, a $c\bar{s}$ hybrid, or a two-meson molecule [13]. In this section we consider the conventional $c\bar{s}$ options for the $D_{sJ}^*(2632)$ [13].

The most plausible $c\bar{s}$ state is the $2^3S_1(c\bar{s})$ state with $M = 2730$ MeV although the $1^3D_1(c\bar{s})$ is somewhat higher with a mass of 2900 MeV [15]. As suggested with respect to the $D_{sJ}^*(2317)$

and $D_{sJ}(2460)$ states, the $q\bar{q}$ predictions could be shifted through mixing with the two-meson continuum. Note that the mass of the $K^*(1410)$ is also lower than quark model predictions and its partial widths also disagree with decay models. So it is possible that the discrepancies of the $K^*(1410)$ and $D^*_{sJ}(2632)$ properties are somehow related.

The allowed open flavour decay modes of a $2^3S_1(c\bar{s})$ state with mass $M = 2632$ MeV are DK, $D_s\eta$, and D^*K. We found that $\Gamma(D^*_{sJ}(2632)) = 36$ MeV with $\Gamma(D^*K) > \Gamma(DK) >> \Gamma(D_s\eta)$. In particular $\Gamma(DK)/\Gamma(D_s\eta) \simeq 9$. For comparison, SELEX finds $\Gamma(D^0K^+)/\Gamma(D_s^+\eta) = 0.32 \pm 0.12$, (taking into account D^0K and D^+K^0). Clearly there is an inconsistency. $2^3S_1 - 1^3D_1$ mixing, which could be generated by coupling to decay channels, could alter this ratio but it would require both fine tuning of the mixing angle and of a quark model parameter to an unlikely value. Although this tuning cannot be ruled out we consider it unlikely. We further estimate $\Gamma(2^3S_1(c\bar{s}) \to D_s^*\pi\pi) \simeq 220$ keV implying BR $\geq 1\%$. If the SELEX state is indeed the $2^3S_1(c\bar{s})$ state the D^*K decay mode must be seen. The $D^*_{sJ}(2632)$ should be seen in B-decay, the $D_s\pi\pi$ mode should be present with BR $\geq 1\%$, and the 1^3D_1 state should be $\sim$200 MeV higher in mass.

5. Summary

To summarize, we found that the P-wave charm mesons are well described by the quark model. However, it is important to confirm the broad $j = 1/2$ states and obtain more precise measurements of their properties. The $D^*_{sJ}(2317)$ and $D_{sJ}(2460)$ states have masses lower than expected for the missing 0^+ and 1^+ $j = 1/2$ $c\bar{s}$ states. This may be due to coupling to decay channels but further work is needed. In any case, radiative transitions are a good way of testing the nature of these states.

If the SELEX $D_{sJ}(2632)$ state is the $2^3S_1(c\bar{s})$ state it should decay to D^*K with a sizable branching ratio. The $2^3S_1(c\bar{s}) \to D_s^* + \pi\pi$ decay mode should also be present with a partial width of $\sim$ 220 keV and a BR of $\sim$ 1%. We expect that the $2^3S_1(c\bar{s})$ should be seen in B-decays. The $1^3D_1(c\bar{s})$ should also be present with a mass roughly 200 MeV higher. We encourage experimenters to search for these states in B-decay.

Acknowledgments

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